Gradual and abrupt changes during the Mid-Pleistocene Transition

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Abstract

During the Mid-Pleistocene Transition (MPT), the dominant glacial-interglacial cyclicity as inferred from the marine $\delta^{18}O$ records of benthic foraminifera ($\delta^{18}O_{benthic}$) changed from 41 kyr to 100 kyr years in the absence of a comparable change in orbital forcing. Currently, only two Mg/Ca-derived, high-resolution bottom water temperature (BWT) records exist that can be used with $\delta^{18}O_{benthic}$ records to separate temperature and ice volume signals over the Pleistocene. However, these two BWT records suggest a different pattern of climate change occurred over the MPT—a record from North Atlantic DSDP Site 607 suggests BWT decreased with no long-term trend in ice volume over the MPT, while South Pacific ODP Site 1123 suggests that BWT has been relatively stable over the last 1.5 Myr but that there was an abrupt increase in ice volume at ~900 kyr. In this paper we attempt to reconcile these two views of climate change across the MPT. Specifically, we investigated the suggestion that the secular BWT trend obtained from Mg/Ca measurements on *Cibicidoides wuellerstorfi* and *Oridorsalis umbonatus* species from N. Atlantic Site 607 is biased by the possible influence of $\Delta[CO_3^{2-}]$ on Mg/Ca values in these species by generating a low-resolution BWT record using *Uvigerina* spp., a genus whose Mg/Ca values are not thought to be influenced by $\Delta[CO_3^{2-}]$. We find a long-term BWT cooling of ~2-

3°C occurred from 1500 to ~500 kyr in the N. Atlantic, consistent with the previously generated *C. wuellerstorfi* and *O. umbonatus* BWT record. We also find that changes in ocean circulation likely influenced $\delta^{18}O_{benthic}$, BWT, and $\delta^{18}O_{seawater}$ records across the MPT. N. Atlantic BWT cooling starting at ~1.2 Ma, presumably driven by high-latitude cooling, may have been a necessary precursor to a threshold response in climate-ice sheet behavior at ~900 ka. At that point, a modest increase in ice volume and thermohaline reorganization may have caused enhanced sensitivity to the 100 kyr orbital cycle.

1. Introduction

Variations in the Earth's orbit, and consequently incoming solar radiation, act as a pacemaker for glacial-interglacial cycles [*Hays et al.*, 1976]. During the mid-Pleistocene transition (MPT, ~1.2 to 0.65 Ma) the glacial-interglacial periodicity as recorded by marine $\delta^{18}O$ records of benthic foraminifera ($\delta^{18}O_{benthic}$) changed from primarily 41 to 100 kyr year cycles without any obvious change in external orbital forcing [*Shackleton and Opdyke*, 1976; *Pisias and Moore*, 1981; *Imbrie et al.*, 1992; *Raymo and Nisancioglu*, 2003]. As the 100 kyr eccentricity cycle has a relatively weak effect on incoming solar radiation [*Imbrie et al.*, 1993], feedbacks within the climate system must have amplified the glacial-interglacial response to the 100 kyr cycle. However, after nearly 40 years of research, the processes and mechanisms that caused the MPT remain enigmatic [*Clark et al.*, 2006].

Explanations as to what caused the MPT are diverse (summarized in [*McClymont et al.*, 2013]), and they generally invoke changes in climate boundary conditions such as: (1) gradual global cooling, possibly related to pCO_2 decrease [*Berger and Jansen*, 1994; *Raymo et al.*, 1997], (2) changes in ice sheet dynamics that allow for the build up of large ice sheets [*Clark et* *al.*, 2006; *Elderfield et al.*, 2012], and/or (3) thermohaline circulation reorganization [*Schmieder et al.*, 2000; *Sexton and Barker*, 2012; *Pena and Goldstein*, 2014]. Much of our understanding of the MPT comes from $\delta^{18}O_{benthic}$ records, which reflect a combination of bottom water temperature (BWT) and seawater oxygen isotope composition ($\delta^{18}O_{seawater}$) [*Shackleton*, 1967; *Pisias and Moore*, 1981; *Labeyrie et al.*, 1987; *Maasch*, 1988; *Ruddiman et al.*, 1989; *Saltzman and Maasch*, 1991; *Mudelsee and Schulz*, 1997; *Rutherford and D'Hondt*, 2000; *Lisiecki and Raymo*, 2005; 2007]. Despite years of study and statistical analysis, disagreement still exists as to whether the MPT reflects a gradual transition that started ~1.2 Ma and finished ~0.65 Ma [*Pisias and Moore*, 1981; *Ruddiman et al.*, 1989; *Rutherford and D'Hondt*, 2000; *Clark et al.*, 2006; *Sosdian and Rosenthal*, 2009; *McClymont et al.*, 2013] or represents an abrupt event centered around 0.9 Ma [*Maasch*, 1988; *Mudelsee and Schulz*, 1997; *Elderfield et al.*, 2012]. The timing of the MPT is particularly relevant to evaluating the mechanisms of climate change (e.g., a gradual response of ice to a gradual forcing, an abrupt response of ice to an abrupt forcing event, or a threshold (abrupt) response of ice to long-term gradual climate forcing). Because $\delta^{18}O_{benthic}$ records a number of environmental parameters (global ice volume, BWT, and local hydrography), part of the disagreement over the timing and character of the MPT may be related to the use of different $\delta^{18}O_{benthic}$ records, with local hydrographic effects obscuring global trends in temperature and ice volume in some records [*Clark et al.*, 2006; *Elderfield et al.*, 2012; *Bates et al.*, 2014].

Because $\delta^{18}O_{benthic}$ reflects BWT *and* $\delta^{18}O_{seawater}$ (e.g. ice volume and local hydrography), several environmental signals are imprinted on any given $\delta^{18}O_{benthic}$ record. To isolate BWT and $\delta^{18}O_{seawater}$ components of $\delta^{18}O_{benthic}$ records, the Mg/Ca ratio of benthic foraminiferal calcite is widely used as an independent proxy of BWT on orbital and tectonic timescales [*Lear et al.*, 2000; *Billups and Schrag*, 2002; *Sosdian and Rosenthal*, 2009; *Elderfield et al.*, 2010; 2012].

Currently, only two high-resolution coupled benthic foraminifera Mg/Ca and $\delta^{18}O_{benthic}$ records exist across the MPT and their implications for how global ice volume changed across the MPT disagree. The first record is the N. Atlantic (the Sosdian and Rosenthal (2009) record from Deep Sea Drilling Project (DSDP) Site 607, 41.0° N, 33.0° W, 3427 m water depth), and the second is from the S. Pacific (the Elderfield et al. (2012) record from Ocean Drilling Program (ODP) Site 1123 located on the Chatham Rise, 41.8° S, 171.5° W, 3290 water depth) (Figure 1). The interpretation of Site 607 record has been challenged based on the observation that, in addition to temperature, changes in carbonate ion saturation ($\Delta[CO_3^{2-}]$) could influence Mg/Ca in benthic species thus biasing BWT estimates in some species (e.g. *Cibicidoides wuellerstorfi*; [*Yu and Broecker*, 2010]; but also see [*Sosdian and Rosenthal*, 2010]). The $\Delta[CO_3^{2-}]$ is defined as $[CO_3^{2-}]_{in\ situ} - [CO_3^{2-}]_{saturation}$.

In addition, the distinct differences in implied BWT histories at Sites 607 and 1123 (and thus climate interpretations) also merit further study. For instance, The N. Atlantic Sosdian and Rosenthal (2009) record at Site 607 suggests that significant BWT cooling (~2°C) occurred over an interval of a million years, from ~1.5 to 0.5 Ma. On the other hand, The S. Pacific Elderfield et al. (2012) record from Site 1123 shows relatively constant, near-freezing temperatures over the over the entire 1.5 Myr record. Although a significant volume of global water flows over Chatham Rise, this area is also sensitive to the relative mixture of northern and southern component water masses (Figure 1).

Given that these sites are in different oceans and at different depths, it is possible that they could be characterized by different BWT trends; however, when the Mg/Ca-derived BWTs are subtracted from the $\delta^{18}O_{benthic}$ records at each site, two very different patterns of $\delta^{18}O_{seawater}$ are observed across the MPT implying seemingly contradictory global ice volume histories. Specifically, Site 607 shows no discernible long-term trend in $\delta^{18}O_{seawater}$ across the MPT [*Sosdian and Rosenthal*, 2009], whereas Site 1123 record shows an abrupt increase occurring at ~900 ka, which Elderfield et al. [2012] attributes to an large expansion of Antarctic ice volume. Instead of global cooling of the deep ocean across the early Pleistocene, the site 1123 record was interpreted as suggesting that an abrupt change in ice sheet dynamics and/or ice volume increase may have been the primary cause of the MPT.

Here we revisit DSDP Site 607 and generate a Mg/Ca-derived BWT record from 500 to 1500 ka using mixed *Uvigerina* spp.. We compare this record to the previous published *C. wuellerstorfi and Oridorsalis umbonatus* record [*Sosdian and Rosenthal*, 2009] in order to evaluate long-term changes in N. Atlantic BWT over the MPT. We also evaluate the possible influence of $\Delta[CO_3^{2-}]$ on Mg/Ca BWT reconstructions based on *Uvigerina* spp., *C. wuellerstorfi and Oridorsalis umbonatus.* We compare $\delta^{18}O_{benthic}$, BWT and $\delta^{18}O_{seawater}$ records from Site 607 with those from Site 1123 in the S. Pacific. Lastly, we consider how changes in ocean circulation could influence the interpretation of $\delta^{18}O_{benthic}$, BWT and $\delta^{18}O_{seawater}$ records from these two sites.

3. Materials and methods

Mg/Ca were measured on mixed *Uvigerina* spp. from DSDP 607 to estimate bottom water temperature. Previous calibration studies suggests that the Mg/Ca ratios of infaunal species such as *Uvigerina* spp. primarily respond to temperature [*Elderfield et al.*, 2010] and show very little $\Delta[CO_3^{2-}]$ effect [*Yu and Elderfield*, 2007]. $\Delta[CO_3^{2-}]$ approaches zero at shallow depths within the sediment because pore waters come to rapid equilibration with calcium carbonate, regardless as to whether the bottom water $\Delta[CO_3^{2-}]$ is oversaturated or undersaturated at particular location [*Elderfield et al.*, 2006]. By contrast, calibration studies suggest that the Mg/Ca ratios of epifaunal species such as *Cibicidoides wuellerstorfi* respond to both temperature and changes in $\Delta[CO_3^{2-}]$ [*Elderfield et al.*, 2006; *Yu and Elderfield*, 2007; *Elderfield et al.*, 2010], possibly resulting in biased temperature reconstructions in areas with markedly large changes in bottom water $\Delta[CO_3^{2-}]$ [*Yu and Broecker*, 2010]. Thus, it is hypothesized that Mg/Ca measurements derived from *Uvigerina* spp. would more accurately reflect BWT variations through time [*Elderfield et al.*, 2010; 2012].

Uvigerina spp. specimens were picked from the >150 μm size fraction with approximately 5-15 specimens analyzed per sample, with a median of 7 specimens per sample. The average sampling resolution is one sample every ~9,000 years. The *Uvigerina* spp. measurements are relatively uniformly distributed between glacial and interglacial periods (Supplemental Figure 1). The vast majority (>88%) of the samples are from the same core samples that were used to generate the *Ruddiman et al.*, [1989] $\delta^{18}O_{benthic}$ record. Samples were cleaned using standard analytical procedures [*Rosenthal et al.*, 1999; *Martin and Lea*, 2002] - samples were repeatedly rinsed in water and methanol to remove clays and cleaned with reductive and oxidative reagents. Owing to small sample weights (~100 μg), not all samples were subjected to a weak acid leaching. Elemental measurements were made either at Lamont-Doherty Earth Observatory (LDEO) on a Thermo Scientific iCAP-Q inductively coupled plasma mass spectrometer (ICP-MS) or at Rutgers University on a Finnigan Element-XR ICP-MS. Al/Ca, Fe/Ca, Mn/Ca and Ti/Ca (Supplemental Figure 2) were used to monitor samples for contamination due to diagenetic overprinting or to residual detrital material (n = 6 samples removed) [*Rosenthal et al.*, 1999]. We find no obvious downcore trends in Mg/Ca and Al/Ca, Fe/Ca, and Ti/Ca. Mn/Ca values are generally high (μ = 126.5 µmol/mol σ = 53.56 µmol/mol) and correlate with Mg/Ca (R^2 = 0.33, <0.001). These high Mn/Ca values do not appear to be due to Mn-Fe oxide and $MnCO_3$ contamination because all samples were reductively cleaned and we found that that after repetitive weak acid leaches, the Mn/Ca values remained relatively high within a subset of samples. There is a weak correlation downcore between Mn/Ca and Mg/Ca but we believe this is a coincidence not caused by the same process. Elderfield et al. [2012] see a similar weak correlation downcore at Site 1123 between Mn/Ca and Mg/Ca that they attribute to diagenetic reorganization. A similar process may have occurred at Site 607.

Instrumental precision at LDEO and Rutgers was 0.5-1%. Long-term precision of a liquid consistency standard at LDEO and Rutgers University was between 1-2%. At LDEO, reproducibility of three consistency standards with Mg/Ca of 1.4840, 4.1325, 8.1035 mmol/mol were ±1.3%, ±1.8%, and ±1.7%, respectively. At Rutgers University, reproducibility of consistency standards with Mg/Ca of 1.25, 3.32, and 7.51 mmol/mol were ±1.2%, ±1.2%, and ±0.6%, respectively. To ensure inter-laboratory accuracy, standards from Rutgers University were run at LDEO. Inter-laboratory accuracy was found to be 3.0%, within the range of previously reported inter-laboratory comparisons [*Rosenthal et al.*, 2004].

There are several species-specific calibrations to choose from to account for known differences in temperature sensitivity and offsets for various benthic foraminifera species [*Lear et al.*, 2002; *Healey et al.*, 2008; *Yu and Elderfield*, 2008; *Sosdian and Rosenthal*, 2009; *Elderfield et al.*, 2012; *Cappelli et al.*, 2015]. For ease of comparison with the site 1123 *Uvigerina* spp. record, we use a modified version of the temperature equation, and the same $\delta^{18}O$ equation, as used by Elderfield et al. (2010, 2012). To correct for known Mg loss during the reductive step [*Barker et al.*, 2003; *Rosenthal et al.*, 2004] used in our cleaning procedure, we adjusted the Elderfield *Uvigerina* spp. paleotemperature equation by 10%: Mg/Ca = 0.9 + 0.1*BWT. Previously published *Cibicidoides wuellerstorfi, and Oridorsalis umbonatus* paleotemperature equations were used for further BWT comparisons between species and to account for species offsets [*Sosdian and Rosenthal*, 2009]. Finally, to estimate $\delta^{18}O_{seawater}$, we used the published $\delta^{18}O_{benthic}$ record [*Ruddiman et al.*, 1989], the Mg/Ca-derived BWT, and the $\delta^{18}O_{seawater}$ equation: $\delta^{18}O_{seawater} = \delta^{18}O_{benthic} + 0.27 - 0.25*(16.9 - BWT)$ [*O'Neil et al.*, 1969; *Shackleton*, 1974; *Kim and O'Neil*, 1997; *Elderfield et al.*, 2010; 2012].

To investigate changes in ocean circulation across the MPT we use previously published $\delta^{13}C$ values of benthic foraminifera ($\delta^{13}C_{benthic}$) (Table 1) and calculated the percent Northern Component Water (%NCW) [*Oppo and Fairbanks*, 1987; *Raymo et al.*, 1990; *Flower et al.*, 2000; *Venz and Hodell*, 2002]. The %NCW is used to estimate the relative contribution of deep water formed in the N. Atlantic (i.e. North Atlantic Deep Water, NADW) at a particular site [*Oppo and Fairbanks*, 1987] and is calculated using the following equation:

$$\%NCW = \frac{\delta^{13}C_{SITE} - \delta^{13}C_{SCW}}{\delta^{13}C_{NCW} - \delta^{13}C_{SCW}} * 100$$

where the $\delta^{13}C_{SITE}$ is the $\delta^{13}C_{benthic}$ value at a given location of interest and $\delta^{13}C_{NCW}$ and $\delta^{13}C_{SCW}$ are the $\delta^{13}C_{benthic}$ values at the designated northern and southern (i.e. Antarctic Bottom Water) water mass end-member locations. Here, we use ODP Site 982 and ODP 1090 as a North Atlantic and South Atlantic end-member, respectively [*Venz and Hodell*, 2002].

4. Results and Discussion

4.1 Comparison of Uvigerina **spp.***, Cibicidoides wuellerstorfi, and Oridorsalis umbonatus records at DSDP Site 607*

The new Mg/Ca record derived from *Uvigerina* spp. at Site 607 shows a decreasing trend from 1500 to 500 kyrs (Figure 2). The *Uvigerina* spp. Mg/Ca record has a similar long-term trend and variability to the previously published *Cibicidoides wuellerstorfi, and Oridorsalis umbonatus* Mg/Ca records [*Sosdian and Rosenthal*, 2009]. Uncertainty in Mg/Ca values is based on the 95% confidence of Monte Carlo error propagation (1000 resampling, $\sigma = 0.128$ mmol/mol for *Uvigerina* spp., this study and $\sigma = \sim 0.1$ for *Cibicidoides wuellerstorfi, and Oridorsalis umbonatus Sosdian and Rosenthal*, [2009]. Offsets in Mg/Ca values are likely related to vital effects.

Large changes in deep ocean chemistry occurred over the MPT [*Raymo et al.*, 1997; *Lisiecki*, 2014] as evidenced from the $CaCO_3$ [*Ruddiman et al.*, 1989], $\delta^{13}C_{benthic}$ [*Ruddiman et al.*, 1989] and %NCW (Figure 2) at Site 607, changes which may have influenced *C. wuellerstorfi* and *O. umbonatus* Mg/Ca values [e.g. Yu and Broecker, 2010]. Specifically, after ~900 kyr a step change in deep ocean chemistry is suggested by an increased amplitude of variability in $CaCO_3$, $\delta^{13}C_{benthic}$, and %NCW, as well as a greater contribution of low $[CO_3^{2-}]$ SCW water at Site 607, particularly during glacial periods. However, given the similarity in the overall long-term Mg/Ca trends in *Uvigerina* spp., *C. wuellerstorfi* and *O. umbonatus*, if *Uvigerina* spp. Mg/Ca values primarily respond to changes in temperature [*Elderfield et al.*, 2010; 2012], then much of the long-term trend in *C. wuellerstorfi* and *O. umbonatus* Mg/Ca values (Figure 2) may also be explained by temperature and not by long-term changes in deep sea carbon chemistry (i.e. changes in $[CO_3^{2-}]$) during the 1500 to 500 kyr time interval at Site 607.

Additionally, we performed an F test to determine whether the large amplitude changes in deep ocean chemistry after ~900 kyr also influenced the variability in Mg/Ca values of

O. umbonatus, C. wuellerstorfi and *Uvigerina* spp.. We compared the Mg/Ca values between the 600 – 800 ka and 1000 – 1250 ka, intervals of large and small amplitude changes in deep ocean chemistry, respectively, for each species and found no statistical difference Mg/Ca variability prior to or after ~900 kyr (Table 1). The lack of coherence and synchronicity in the long-term trend and variability between Mg/Ca and the deep ocean chemistry parameters suggests changes in [CO_3^{2-}] do not dominate benthic foraminifera Mg/Ca values during the MPT at Site 607 [*Sosdian and Rosenthal*, 2009; 2010].

The new BWT record derived from *Uvigerina* Mg/Ca values at Site 607 shows a decreasing trend in mean temperature of ~2-3°C from 1500 to 500 kyr (Figure 3), regardless of calibration choice, suggesting a long-term cooling of bottom waters occurred. In Figure 3, *O. umbonatus, C. wuellerstorfi* and *Uvigerina* spp. Mg/Ca values were converted to temperature using available low-temperature species-specific temperature calibrations [*Lear et al.*, 2002; *Healey et al.*, 2008; *Yu and Elderfield*, 2008; *Sosdian and Rosenthal*, 2009; *Elderfield et al.*, 2012; *Cappelli et al.*, 2015]. The magnitude of long-term temperature cooling between 1500 to 500 kyr is dependent on calibration choice with *C. wuellerstorfi* broadly showing less cooling than *O. umbonatus* and *Uvigerina* spp.. These differences in temperature reconstructions are not related to changes in the presence or absence of different species during interglacial and glacial periods as the species are generally found throughout the 1500 to 500 kyr interval (see Supplemental Figure 1 for *Uvigerina* spp. distribution). The previously published Mg/Ca records of *O. umbonatus* and *C. wuellerstorfi* [*Sosdian and Rosenthal*, 2009] suggest a ~2°C and ~1-2°C cooling trend from 1500 to 500 kyr respectively, depending on calibration choice, which is in broad agreement with the *Uvigerina* spp. record (Figure 3). Additionally, all species show a similar magnitude of cooling at the warm and cold range of temperatures which suggests there was a similar magnitude of cooling in the interglacial and glacial intervals over the MPT [*Sosdian and Rosenthal*, 2009]. Likewise, for the late Pleistocene, the previously published *O. umbonatus* and *C. wuellerstorfi* records are in good agreement with an ostracode Mg/Ca-BWT record [*Dwyer et al.*, 1995], though there is also disagreement as to whether ostracode Mg/Ca values also respond to changes $\Delta[CO_3^{2-}]$ [*Elmore et al.*, 2012; *Farmer et al.*, 2012]. Regardless of species-specific calibration choice, the *Uvigerina* spp., *O. umbonatus* and *C. wuellerstorfi* records show a similarly decreasing BWT trend over the MPT.

Based on the above observations, we combine the *Uvigerina* spp., *C. wuellerstorfi* and *O. umbonatus* data to create a composite BWT record at Site 607 (Figure 4A). Mg/Ca values for each species were converted to temperature using the species-specific paleotemperature equations [*Sosdian and Rosenthal*, 2009; *Elderfield et al.*, 2010; 2012] to account for species offsets and Mg/Ca-temperature sensitivities. Using the *Uvigerina* spp. BWT generated in this study and the previously published $\delta^{18}O_{benthic}$ record [*Ruddiman et al.*, 1989], paired $\delta^{18}O_{seawater}$ values were calculated (blue dots, Figure 4B). We then combine our *Uvigerina* spp.-derived $\delta^{18}O_{seawater}$ values with the previously published *C. wuellerstorfi* and *O. umbonatus*-derived $\delta^{18}O_{seawater}$ values [*Sosdian and Rosenthal*, 2009] to create a composite $\delta^{18}O_{seawater}$ record (Figure 4). We note that during the early Pleistocene some warm BWT estimates result in reconstructed $\delta^{18}O_{seawater}$ values approaching +1.5‰, which seems unlikely considering the early Pleistocene is thought to have had less ice than the recent glacial period. Part of the issue may be that several species of benthic foraminifera are used in these reconstructions (e.g. the $\delta^{18}O_{benthic}$ is based on *C. wuellerstorfi* and the BWT is based on *Uvigerina* spp.) or that BWT and $\delta^{18}O_{benthic}$ records are not in phase (i.e. temperature leads ice volume, *Sosdian and Rosenthal*, [2009]). To account for the fact that these records are based on different species with different temperature and $\delta^{18}O$ sensitives, the composite BWT and $\delta^{18}O_{seawater}$ records were smoothed using a three point moving to reduce the error on the estimates (see Supplemental Text). By smoothing the records, we can focus on our primary goal of understanding the long-term trends in BWT and $\delta^{18}O_{seawater}$. The advantage of combining *Uvigerina* spp., *C. wuellerstorfi* and *O. umbonatus* analyses is that we are able to achieve a more continuous, high-resolution record because these species often alter in abundance with *Uvigerina* being generally more abundant during glacial periods.

Interestingly, over the same period, the $\delta^{18}O_{benthic}$ record at Site 607 has a decreasing trend of 0.317‰ (Figure 5), which is equivalent to a ~1.3°C cooling using a sensitivity of 0.25‰ per °C. A combination of possibilities could explain this trend: 1) the $\delta^{18}O_{benthic}$ record is dominated by BWT cooling and there was little ice volume increase over the MPT, 2) there was a change in ice sheet end member values and thus mean ocean $\delta^{18}O_{seawater}$ (e.g. [*Winnick and Caves*, 2015]), and/or 3) changes in ocean circulation may influence the $\delta^{18}O_{seawater}$ values at Site 607. Due to the variable constraints on $\delta^{18}O_{seawater}$ and the large error on the $\delta^{18}O_{seawater}$ estimate, we do not intend to reconstruct sea level and instead focus on the long-term trends in BWT and $\delta^{18}O_{seawater}$ at Site 607.

4.2. Comparison of Site 607 and Site 1123 BWT records

The BWT, $\delta^{18}O_{benthic}$ and $\delta^{18}O_{seawater}$ records at Sites 607 and 1123 have dissimilar long-term trends from 1500 to 500 kyr (Figure 5). While Site 607 shows a subtle yet distinct long-term BWT cooling trend from 1500 to ~500 kyr (taking into account uncertainties discussed in previous section; Figure 4, 5), Site 1123 data show colder, near freezing temperatures characterizing the entire 1500 kyr record (Figure 5) [*Elderfield et al.*, 2012]. The $\delta^{18}O_{benthic}$ records at Sites 607 and 1123 correlate well with the globally averaged benthic oxygen isotope LR04 stack [*Lisiecki and Raymo*, 2005] (Figure 5) except during the glacial periods between MIS 22 and MIS 18 when Site 1123 shows a pronounced ~0.3 to 0.5‰ increase during glacial periods relative to LR04. At MIS 16 the $\delta^{18}O_{benthic}$ records converge again.

Site 607 $\delta^{18}O_{seawater}$ values show no change in the long-term mean or amplitude from 1500 to 500 kyr (Figure 4, 5). On the other hand, at Site 1123, $\delta^{18}O_{seawater}$ values show an increase in the mean and the amplitude after MIS 22 (Figure 5). The site 1123 $\delta^{18}O_{seawater}$ record has been interpreted as showing a large build up of ice volume at MIS 22 [*Elderfield et al.*, 2012], relative to the earlier interval, whereas the Site 607 $\delta^{18}O_{seawater}$ record shows no obvious, abrupt increase in ice volume occurred at MIS 22. If there was a large increase in glacial ice volume at MIS 22, relative to earlier intervals, as Elderfield et al. (2012) suggests, then it is difficult to reconcile the different $\delta^{18}O_{seawater}$ records at Site 1123 and 607 because a large increase in ice volume should be common to both records. This suggests that hydrographic changes may have occurred over the MPT at one or both sites, changes that could have influenced the $\delta^{18}O_{seawater}$. In the next sections we explore possible hydrographic changes at Sites 1123 and 607.

4.3. Teasing apart local changes in ocean circulation and global climate

$\delta^{18}O_{seawater}$ values depend *globally* on the build-up/loss of ^{16}O on the continents on glacial-interglacial time scales and *locally* on water that flows over any abyssal location, integrating both global climate and regional bottom water properties imprinted by high latitude deep-water formation and ocean circulation. One implication of the Elderfield et al., [2012] record is that if the Site 1123 $\delta^{18}O_{seawater}$ is assumed to be the global $\delta^{18}O_{seawater}$ signal (as suggested by those authors), then the residual $\delta^{18}O_{benthic}$ temperature component in the LR04 stack as well as in the Sites 607, 1020, 1146, 1143, 846, 849 $\delta^{18}O_{benthic}$ records would suggest a warming of the deep Atlantic and Pacific water of nearly 2°C (e.g., ~0.5‰, assuming 0.25‰/°C) occurred during glacial MIS 22 (Figure 5). Indeed, if Elderfield et al.'s [2012] conclusions about global ice volume are correct, then these sites would seemingly reflect bottom water warming during glacial periods across the MPT, until MIS 16 when the $\delta^{18}O_{benthic}$ converge again (Figure 5). It is difficult to explain why large expanses of the deep Atlantic and Pacific oceans would be warming during glacial excursions across the MPT. Here we suggest that changes in ocean circulation may influence the magnitude of the abrupt change observed at Site 1123 and the record reflects both global and local changes. Numerous studies have documented changes in deep ocean circulation over the MPT using $\delta^{13}C$ of benthic foraminifera [*Raymo et al.*, 1997; *Venz et al.*, 1999; *Venz and Hodell*, 2002; *Hodell et al.*, 2003; *Ferretti et al.*, 2010; *Poirier and Billups*, 2014] and carbonate preservation [*Schmieder et al.*, 2000; *Sexton and Barker*, 2012]. Here we examine how these circulation changes may have influence the $\delta^{18}O_{benthic}$ and Mg/Ca-derived $\delta^{18}O_{seawater}$ records from Site 1123 and 607.

4.3.1. Changes in ocean circulation from MIS 24 to 22

The $\delta^{18}O_{benthic}$ record at Site 1123 (and thus also the calculated $\delta^{18}O_{seawater}$ record) stands out as anomalous in comparison to the LR04 stack (Figure 5). Elderfield et al. [2012] argue that Site 1123 is representative of global conditions because a large volume of water flows over the Chatham Rise and into the Pacific (Figure 1) and LR04 is not representative of global conditions because it is biased to the Atlantic Ocean; however, Site 1123 $\delta^{18}O_{benthic}$ values are different from many of the records from the rest of the Pacific basin. In comparison to the previously published high-resolution mid-to-deep (i.e. >2000 m water depth, Table 2) $\delta^{18}O_{benthic}$ records from the South China Sea, California Margin, and equatorial Pacific (Figure 6), Site 1123 is ~0.4‰ heavier than most of the other Pacific records. Although Elderfield et al. [2012] point out Site 1123 shows good agreement with Site 677, Site 677 is located in the Panama Basin (sill depth 2300 to 2920 m [*Lonsdale*, 1977]) and is bathymetrically isolated from the rest of the deep eastern equatorial Pacific. The other Pacific records, including those from the deep eastern equatorial Pacific (e.g. Sites 846 and 849, water depth 3307 and 3849 m, respectively), show good agreement with LR04. The choice of benthic species used in generating the $\delta^{18}O_{benthic}$ records also does not appear to contribute to these discrepancies. Although many of these $\delta^{18}O_{benthic}$ records are based on C. *wuellerstorfi* or a mixture of C. *wuellerstorfi* and *Uvigerina* spp., as Elderfield et al. [2012] note, at Site 1123 during MIS 22, the abrupt shift in $\delta^{18}O_{benthic}$ is observed in both C. *wuellerstorfi* and *Uvigerina* spp. samples. The similarity between C. *wuellerstorfi* and *Uvigerina* spp. $\delta^{18}O_{benthic}$ samples appears to hold for the rest of the Pacific. Consequently, we infer that the very positive $\delta^{18}O_{benthic}$ excursions at MIS 22 at Sites 677 and 1123 may reflect a local hydrographic effects, possibly due to the time-varying mixing of different water masses, that are not recorded in the rest of the Pacific basin (Figure 1).

In the Atlantic, the relative importance of NCW and SCW changed over the MPT [*Raymo et al.*, 1997; *Venz and Hodell*, 2002; *Hodell et al.*, 2003; *Pena et al.*, 2008; *Lisiecki*, 2014]. Significant changes in ocean circulation over the MPT may have created hydrographic conditions unique to Site 1123 that are not representative of deep Pacific Ocean or global conditions. This change could have had downstream consequences for the Pacific because a mixture of SCW and NCW flows into the deep Pacific [*Hall et al.*, 2001; *Elderfield et al.*, 2012].

We suggest that Site 1123 $\delta^{18}O_{seawater}$ record is likely not representative of mean ocean $\delta^{18}O_{seawater}$ because its location on the Chatham Rise appears to be sensitive to the mixing ratio of SCW and NCW (Figure 1).

In Figure 7, $\delta^{13}C_{benthic}$ and %NCW records show marked changes in glacial deep ocean circulation in the Atlantic across the MPT (for completeness, the Pacific basin can be found in Supplemental Figure 3). Prior to MIS 24, NCW filled the Atlantic above ~3500m during glacial periods [*Raymo et al.*, 1997; *Venz and Hodell*, 2002; *Hodell et al.*, 2003; *Pena et al.*, 2008; *Lisiecki*, 2014]. Beginning at MIS 24 and intensifying at MIS 22, Nd isotopes and $\delta^{13}C_{benthic}$ from intermediate and deep water horizons suggest bottom waters were predominantly ventilated by SCW [*Raymo et al.*, 1997; *Venz and Hodell*, 2002; *Hodell et al.*, 2003; *Pena et al.*, 2008; *Lisiecki*, 2014; *Poirier and Billups*, 2014]. These changes in Atlantic circulation may be related to an observed decrease in the mean flow speed over the Chatham Rise starting at MIS 22 (e.g. Site 1123; [*Hall et al.*, 2001; *Venuti et al.*, 2007]), a hydrographic change which may have contributed to the unique $\delta^{18}O_{benthic}$ signal recorded at Site 1123.

This change in Atlantic deep ocean circulation likely influenced the Site 607 $\delta^{18}O_{benthic}$ record as well as the records throughout the Atlantic. Elderfield et al. [2012] point out Site U1308 also shows an abrupt increase in $\delta^{18}O_{benthic}$ at MIS 22 which is similar to Site 1123 (Figure 8). However, this abrupt increase in $\delta^{18}O_{benthic}$ is absent in the Site 607 and LR04 records. Although Sites 607 and U1308 are both in the N. Atlantic, they experience different water masses because they are on different sides of the basin separated by the mid-Atlantic ridge. Site 607 is in the western Atlantic basin and ventilated by either NCW and SCW whereas U1308 is in the eastern Atlantic basin which is ventilated from the south by a mixture of NCW and SCW that flows over the Romanche Fracture Zone at the equator [*Raymo et al.*, 1997]. The value of using a stacked record like LR04 is that it changes in hydrography are mostly averaged out. The LR04 stack, though biased toward the Atlantic, has at least 23 records that on average do not show an abrupt change in $\delta^{18}O_{benthic}$ at MIS 22. The LR04 stack combined with the observations in the Pacific this suggests that an abrupt, large magnitude change at MIS 22 is likely related to changes in ocean circulation ventilating that particular area rather than whole ocean changes in $\delta^{18}O$ related to ice volume.

4.3.2 Long-term cooling at Site 607

The cause of the long-term bottom water cooling found in at Site 607 and its relationship to the emergence of the 100 kyr cycle remains elusive. Long-term cooling that begins or intensifies at ~1.2 Ma is found in multiple mid- to high latitude sea surface temperature records [*Lawrence et al.*, 2010; *McClymont et al.*, 2013], suggesting that this long-term secular cooling trend is not limited to the deep ocean. Although this trend is observed in a number of surface locations in the N. Atlantic, the BWT cooling trend observed at Site 607 could also be due to cold, southern component waters gradually penetrating further into the N. Atlantic over the MPT. $\delta^{13}C_{benthic}$ records from deep North Atlantic locations show gradually decreasing values starting at ~1.1 Ma [*Raymo et al.*, 1990; 1997; 2004; *Ferretti et al.*, 2005; *Lisiecki*, 2014; *Poirier and Billups*, 2014] consistent with an increasing contribution of an isotopically light, southern-sourced water mass. It is likely that the BWT cooling observed at Site 607 reflects both cooling in the deep ocean and changing deep ocean circulation, such as increasing influence of southern component waters [*Sosdian and Rosenthal*, 2009] as shown in Figure 7.

4.3.3 Long-term and Threshold Climate Change across the Mid-Pleistocene Transition

It is clear from the gradual BWT cooling at Site 607 as well as the abrupt changes at Site 1123 that the MPT exhibited both gradual and threshold-like responses to climate forcing. Gradually changing environmental conditions (summarized by *McClymont et al.*, [2013]), including N. Atlantic BWT and mid- to high-latitude SST cooling [this study, *Sosdian and Rosenthal*, 2009; *Lawrence et al.*, 2010; *McClymont et al.*, 2013], expanded sea-ice coverage [*Kemp et al.*, 2010], equatorward polar front migration [*McClymont et al.*, 2008; *Lawrence et al.*, 2010; *Martinez-Garcia et al.*, 2010], decreased deep ocean ventilation [*Hall et al.*, 2001; *Venuti et al.*, 2007], intensified ocean/atmospheric circulation [*de Garidel-Thoron et al.*, 2005; *McClymont and Rosell-Mele*, 2005], and increased ice-sheet size [*Clark et al.*, 2006] may have altered climate boundary conditions in a way that shifted the cryosphere across a threshold that permanently altered climate–ice sheet response to orbital forcing. Centered on this long-term trend, the LR04 $\delta^{18}O_{benthic}$ stack shows a ~0.15‰ increase at MIS 22 (~900 ka, Figure 5), likely related to ice volume growth, and a statistically significant emergence of the 100 kyr cycle [*Maasch*, 1988; *Mudelsee and Stattegger*, 1997; *Clark et al.*, 2006; *Raymo et al.*, 2006; *Lisiecki and Raymo*, 2007; *McClymont et al.*, 2013]. As southern Hemisphere summer insolation was anomalously low during the MIS 24 to 22 interval, this ice volume growth may have occurred in Antarctica (as suggested by [*Raymo et al.*, 2006] and Elderfield et al. [2102]). However, we suggest the ice volume growth is not to the magnitude implied by record at Site 1123 (~0.3‰ $\delta^{18}O_{seawater}$) due to possible local hydrographic effects as discussed above. Additional globally distributed, high-resolution $\delta^{18}O_{seawater}$ records are needed to fully deconvolve the influence of ice volume and circulation changes during the MIS 24 to MIS 22 transition.

As with the glacial cycles that characterize the late Pleistocene [*Shakun et al.*, 2015], ice sheets may be a largely responding to changes in global temperatures and atmospheric CO_2 on glacial-interglacial time scales and these ice sheets may have had a threshold response to global cooling during the MPT. For example, ice volume may have switched from a 41 kyr to a 100 kyr orbital signal because global SSTs underwent a similar transition during the MPT: SSTs are dominated by 41 kyr cycles during the early Pleistocene [*Herbert et al.*, 2010; *McClymont et al.*, 2013] and the 100 kyr cycle slowly emerges at ~1.2 Ma [*McClymont et al.*, 2013] and fully dominates at ~900 ka [*Medina-Elizalde and Lea*, 2005; *McClymont et al.*, 2013]. However, invoking a 41 kyr to 100 kyr transition in SST change as the mechanism for forcing the 41 kyr to 100 kyr transition in $\delta^{18}O_{benthic}$ records just moves the question of "why" to another proxy.

It is possible that thermohaline circulation reorganization [*Pena and Goldstein*, 2014] and the increased influence of the southern ocean in deep water circulation [*Raymo et al.*, 1997; 2004; *Ferretti et al.*, 2005; *Lisiecki*, 2014; *Poirier and Billups*, 2014] may have altered heat and salt transport and carbon cycling in the deep ocean. At ~900 ka, the BWT and $\delta^{18}O_{seawater}$ records at Site 607 and 1123 converge (Figure 5) suggesting enhanced connectivity between the Atlantic and Pacific ocean basins. High-resolution atmospheric CO_2 estimates and records of deep ocean chemistry are necessary to fully understand the links between temperature, ocean circulation, CO_2, ice volume during the MPT.

5. Summary

We have reconstructed a Mg/Ca-derived BWT record using *Uvigerina* spp. from DSDP Site 607 that shows an ~2-3 °C cooling from ~1500 to 500 kyrs across the MPT. This gradual cooling trend is consistent with a previously published BWT record based on *C. wuellerstorfi* and *O. umbonatus* [*Sosdian and Rosenthal*, 2009] implying that Mg/Ca records based on epifaunal benthic species at Site 607 during the MPT are robust. We hypothesize that thermohaline reorganization at starting at MIS 24 and intensifying at MIS 22 likely influenced the local hydrography at ODP Site 1123, consequently explaining the unusually large decrease in $\delta^{18}O_{seawater}$ at that site. Gradual N. Atlantic BWT and mid- to high-latitude sea surface temperature cooling likely pushed the climate system across a threshold starting at MIS 24. A modest increase in ice volume at ~900 ka, possibly in Antarctica, combined with thermohaline reorganization, created a new climate regime with enhanced sensitivity to the 100 kyr orbital cycle.

Acknowledgements

We would like to thank two anonymous reviewers that greatly improved the quality of the manuscript. Additionally, we would like to thank Stella Woodard and Blake Dyer for helpful discussions, Katherine Esswein for analytical support and Bilal Nadeem, Andrés Salazar and Jason Swann for laboratory assistance. Marine sediment samples were provided as part of the International Ocean Discovery Program (IODP). Funding was provided by NSF grant OCE-1436014 (HLF and MER).

Table 1. F-test statistics comparing Mg/Ca values of *C. wuellerstorfi* and *O. umbonatus* and *Uvigerina* spp. between the 600 – 800 ka and 1000 – 1250 ka. No statistical difference in Mg/Ca variability is observed prior to or after MIS 22.

	F-test	Degrees of Freedom Numerator	Degrees of Freedom Denominator	P value
C. wuellerstorfi	1.5128	47	31	0.2251
O. umbonatus	0.7160	16	24	0.4948
Uvigerina spp.	1.0393	30	37	0.9027

Table 2. Core Locations of Previously Published Benthic Stable Isotope Values.

Site	Latitude	Longitude	Water Depth (m)	$\delta^{18}O$ and $\delta^{13}C$ Reference	$\delta^{13}C$ Reference	$\delta^{18}O$ Reference
Atlantic						
GIK13519	5.7 N	19.9 W	2862	[*Sarnthein et al.*, 1994]		
GeoB1034	21.7 S	5.4 E	3731	Bickert and Wefer [1996]		
GeoB1211	24.5 S	7.5 E	4089	Bickert and Wefer [1996]		
DSDP 552	56 N	23.2 W	2301	[*Shackleton and Hall*, 1984]		
DSDP 607	41 N	33 W	3427	[*Ruddiman et al.*, 1989]		
ODP 664	0.1 N	23.2 W	3806	[*Raymo et al.*, 1997]		
ODP 925	4.2 N	43.5 W	3040	[*Bickert et al.*, 1997]		
ODP 926	3.7 N	42.9 W	3598	[*Lisiecki et al.*, 2008]		
ODP 927	5.5 N	44.5 W	3326	[*Bickert et al.*, 1997]		
ODP 928	5.5 N	43.7 W	4012	[*Lisiecki et al.*, 2008]		
ODP 929	6 N	43.7 W	4369	[*Bickert et al.*, 1997]		
ODP 980	55.5 N	14.7 W	2179	[*Flower et al.*, 2000]		
ODP 981	55.5 N	14.7 W	2173	[*Raymo et al.*, 2004]		
ODP 982	57.5 N	15.9 W	1146	[*Venz et al.*, 1999; *Venz and Hodell*, 2002]		
ODP 983	60.4 N	23.6 W	1983	[*Raymo et al.*, 2004]		
ODP 984	61.4 N	24.1 W	1650	[*Raymo et al.*, 2004]		
ODP 1063	33.7 N	57.6 W	4584	[*Ferretti et al.*, 2005; *Poirier and Billups*, 2014]		
ODP 1088	41.1 S	13.6 E	2081	[*Hodell et al.*, 2003]		
ODP 1089	40.9 S	9.9 E	4621	[*Hodell et al.*, 2001]		
ODP 1090	42.9 S	8.9 E	3699	[*Venz and Hodell*, 2002]		
ODP 1264	28.5 S	2.8 E	2505	[*Bell et al.*, 2014]		
ODP 1267	28.1 S	1.7 E	4355	[*Bell et al.*, 2014]		
IODP U1308	49.9 N	24.2 W	3871	[*Hodell et al.*, 2008]		
IODP U1313	41 N	33 W	3426	[*Ferretti et al.*, 2010]		
IODP U1314	56.4 N	27.9 W	2820	[*Alonso-Garcia et al.*, 2011]		
Pacific						
GeoB15016	27.5 S	71.1 W	956		[*Martínez-Méndez et al.*, 2013]	
PC72	0.1 N	139.4 W	4298			[*Murray et al.*, 2000]
RC13110	0.1 S	95.7 W	3231	[*Mix et al.*, 1991]		
ODP 677	1.2 N	83.7 W	3461	[*Shackleton et al.*, 1990]		
ODP 806	0.3 N	159.4 E	2520		[*Bickert et al.*, 1993]	
ODP 846	3.1 S	90.8 W	3307	[*Mix et al.*, 1995a]		
ODP 849	0.2 N	110.5 W	3849	[*Mix et al.*, 1995b]		
ODP 1020	41 N	126.4 W	3038			Liu, personal communication to L. Lisiecki [2002]
ODP 1123	41.8 S	171.5 W	3290	[*Hall et al.*, 2001; *Harris*, 2002; *Elderfield et al.*, 2012]		
ODP 1143	9.4 N	113.3 E	2772		[*Cheng et al.*, 2004]	[*Tian et al.*, 2002]
ODP 1146	19.5 N	116.3 E	2091	[*Prell*, 2003]		
ODP 1241	5.8 N	86.4 W	2027	[*Lalicata and Lea*, 2011]		

Figure Captions

Figure 1. Locations of sites: $\delta^{13}C_{benthic}$ from the Atlantic (squares, Table 1), $\delta^{18}O_{benthic}$ from the Pacific (circles, Table 2), and DSDP Site 607 and ODP Site 1123 with Mg/Ca-derived BWT records (stars) (A). Hydrographic transects for Site 607 (B) and Site 1123 (C). Atlantic transect of carbonate ion concentration [CO_3^{2-}] [*Key et al.*, 2004]. Site 607 is in area sensitive to changes in [CO_3^{2-}] on glacial-interglacial time scales. Site 1123 is located in an area sensitive to water mass mixing (panel modified from [*Carter et al.*, 1999]). Figure generated using Ocean Data View [*Schlitzer*] and [*Troupin et al.*, 2012].

Figure 2. DSDP Site 607 Mg/Ca values of *Uvigerina spp.* (blue, this study) and previously published *O. umbonatus* (pink) and *C. wuellerstorfi* (light green) [*Sosdian and Rosenthal*, 2009] (A). Deep ocean chemistry indicators %$CaCO_3$ (B), $\delta^{13}C_{benthic}$ (C) and %NCW (D).

Figure 3. Mg/Ca values converted to BWT using previously published species-specific temperature calibrations of L2002 [*Lear et al.*, 2002], SR2009 [*Sosdian and Rosenthal*, 2009], YE2008 [*Yu and Elderfield*, 2008], C2015 [*Cappelli et al.*, 2015], H2008 [*Healey et al.*, 2008] and E2012 [*Elderfield et al.*, 2012].

Figure 4. All species included for a composite BWT record at Site 607 using the species-specific temperature calibrations of [*Sosdian and Rosenthal*, 2009] and [*Elderfield et al.*, 2012]. (A). Previously published (grey) and new *Uvigerina* spp. (blue, this study) $\delta^{18}O_{seawater}$ values (B). Error bars on the left hand side indicate the 3 point smoothed combined error. Error for BWT

measurements is ±1.4°C and the propagated error for $\delta^{18}O_{seawater}$ estimates is ±0.33‰ (see Supplemental Text).

Figure 5. Comparison of LR04 (black), ODP Site 1123 (A, orange), DSDP Site 607 (B, blue), for $\delta^{18}O_{benthic}$, BWT (C), and $\delta^{18}O_{seawater}$ (D). Site 607 shows a long-term cooling trend over the MPT while Site 1123 has near freezing temperatures over length of the 1.5 Myr record.

Figure 6. Previously published, high-resolution, mid to deep ocean depth $\delta^{18}O_{benthic}$ records from the Pacific plotted in comparison to LR04. ODP Sites 1123 and 677 stand out as anomalous in comparison to most of the records from the Pacific Ocean basin and LR04.

Figure 7. Cross-section view of mean glacial $\delta^{13}C_{benthic}$ values and %NCW for MIS 38 and MIS 26 to MIS 16 for sites in the Atlantic Ocean basin. Figure generated using Ocean Data View [*Schlitzer*]. For completeness, the Pacific Basin is included in Supplemental Figure 2.

Figure 8. Previously published $\delta^{18}O_{benthic}$ records from Sites 607, U1308 and 1123 plotted in comparison to LR04. ODP Sites 1123 and U1308 stand out as anomalous in comparison to Site 607 and LR04.

Supplemental Figure 1. Distribution of *Uvigerina* spp. measurements on the $\delta^{18}O_{benthic}$ record. Over 88% of the Uvigerina spp. samples are directly paired with $\delta^{18}O_{benthic}$ samples.

Supplemental Figure 2. Various elemental to calcium ratios that were used to monitor contamination.

Supplemental Figure 3. Cross-section view of mean glacial $\delta^{13}C_{benthic}$ values and %NCW for MIS 38 and MIS 26 to MIS 16 for sites in the Pacific Ocean basin. These transects were not interpolated as in Figure 5 because the Pacific basin is large and the data is more sparse than in the Atlantic. Figure generated using Ocean Data View [*Schlitzer*].

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